TT-A-642-75-170

June 1975

(12)

ADAC22082

*ASSESSMENT OF POTENTIAL FOR COLLOIDAL FUELS*

TECHNICAL REPORT

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Unclassified

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

**REPORT DOCUMENTATION PAGE**

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER
TT-A-642-75 170

2. GOVT ACCESSION NO.

3. RECIPIENT'S CATALOG NUMBER

6

4. TITLE (and Subtitle)
Assessment of Potential for Colloidal Fuels

9

5. TYPE OF REPORT & PERIOD COVERED
Technical Report,

14 TETRAT

6. PERFORMING ORG. REPORT NUMBER
TT-A-642-75-170

10

7. AUTHOR(s)
Arthur Garcia

15

8. CONTRACT OR GRANT NUMBER(s)
N00014-74-C-0348

9. PERFORMING ORGANIZATION NAME AND ADDRESS
Tetra Tech, Inc.
1911 Ft. Myer Drive
Arlington, VA 22209

10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
N/A

11. CONTROLLING OFFICE NAME AND ADDRESS
Commander
Defense Contract Administration Services Region
P.O. Box 7730
Philadelphia, PA 19101

11

12. REPORT DATE
June 1975

12 55p

13. NUMBER OF PAGES
50

14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)
Scientific Officer
Office of Naval Research
800 N. Quincy Street
Arlington, VA 22217

15. SECURITY CLASS. (of this report)
Unclassified

15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release;
distribution unlimited

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

N/A

18. SUPPLEMENTARY NOTES

N/A

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

N/A

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

N/A

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE
S/N 0102-014-6601

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

# ASSESSMENT OF THE POTENTIAL FOR COLLOIDAL FUELS

by

Tetra Tech, Inc.

June 1975

for

U.S. Navy Energy R&D Office
CDR Paul A. Petzrick, Director
Under ONR Contract N00014-74-C-0348

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## Summary and Conclusions

Colloidal fuels, consisting of a combination of residual fuel oils as the basic carrier with coal added in particulate form have been evaluated throughout the 20th century. They received considerable attention during World War I and II as potential fuel substitutes in the event petroleum sources were interrupted.

The investigation of the potential of colloidal fuels reported herein was stimulated by the issue of a report by Battelle Columbus Laboratories (BCL) on the potential application of colloidal fuels by the DOD. The BCL report ~~(reference~~ 1) indicated that a complete conversion to colloidal fuels could provide DOD fuel savings of 200 to 400 million dollars per year.

The primary conclusion of this reassessment is that the net savings potential of colloidal fuel appears too small and for too limited a market to indicate any significant economic advantage for either DOD or the nation.

However, this conclusion should not preclude pursuing further research of colloidal fuel. Colloidal fuel would be a means of using vast U.S. coal resources to extend limited petroleum energy resources. Colloidal fuels could at least provide an alternate energy source for reducing residual fuel requirements should another fuel crisis occur. The technological base for colloidal fuels should be expanded so that the lag time required to develop the colloidal fuels will not interfere with the eventual or emergency implementation of these alternate fuels. In the interest of establishing the technical foundation to provide the broadest of alternatives to future energy requirements, colloidal fuels should be researched and continually reconsidered for production as the economic environment changes in the future.

The analysis presented for coal-in-oil slurries could also, in general, pertain to residual oil slurries with pulverized petroleum coke or solvent refined coal. Petroleum coke has a greater proportion of sulfur but a lesser proportion of ash than coal has. Coke also has a certain amount of nickel and vanadium which is highly corrosive and which is not present in coal. The low ash characteristic of petroleum coke is particularly important to producing a slurry fuel which will be compatible with residual fuel burning boilers. Petroleum coke currently costs as much as eastern coal and will increase in cost as the undesirable sulfur and destructive minerals are removed. Further, the supply of surplus petroleum coke is limited; therefore, petroleum coke appears less attractive economically or as a substantial resource than coal as the solid fuel component in slurry fuels. Solvent refined coal is low in ash and sulfur and somewhat higher in heating value than coal. This clean fuel is being produced in limited quantities on an experimental basis. As with petroleum coke, solvent refined coal will be a relatively expensive solid fuel component for slurry fuels when compared to feed stock coal.

This report has not specifically addressed the potential of slurries of coal with carriers of water or methanol alcohol. The former is of interest as a transport concept. The fuel would presumably be dried prior to firing to prevent excessive loss of heat content. The latter concept of a methanol carrier has been previously evaluated by Tetra Tech for the U.S. Navy Energy R&D Office. On balance, this concept was found to offer no significant advantages, but to suffer considerable disadvantages in terms of energy delivery per unit weight or volume when compared to slurries based upon hydrocarbon carriers. No economic advantage for the methanol carrier can be shown unless and until the cost of methanol is less than the cost of the hydrocarbon from which it is now conventionally derived.

## Apparent Advantages of Colloidal Fuels

Colloidal fuels should provide moderately priced liquid fuels through the blending of relatively cheap coal with the more expensive petroleum liquid fuels. Western coal costs $12 per ton (nominally) and residual fuel oil costs $12 per barrel (nominally) which is $74 per ton. The proportion of coal that may be blended with residual oil to result in a pumpable liquid fuel is limited to 40% by weight. However, this weight proportion of coal can contribute only 30% of the energy per unit weight of blend because coal has a lower energy density than oil has. At the given cost of coal and oil, the ideal cost of a colloidal blend would be $55 per ton or $9 per barrel. This ideal cost would be a 25% reduction from the cost of residual oil and represents a maximum potential fuel cost savings. As indicated on Table I, when the cost of pulverizing the coal, the cost of blending, plant operating costs and fixed plant capital costs are factored into the cost of producing the colloidal fuel, the realistic savings margin may be half that of the ideal cost savings margin. (Table I is developed in detail in Appendix A). If the cost of coal is $24 per ton, which is the current nominal cost to eastern U. S. states, the ideal savings margin is 20% but the realistic savings margin indicated in Table I is less than 4%.

The cost of pulverizing and grinding the coal is in the order of 3% of the cost of the colloidal product. Plant operating costs are less than 10% of the product cost. This estimate was derived from the operating costs of the simplest petroleum blending operations and should be realistic. Fixed capital costs are also estimated and are very small for the large capacity commercial plant model of Table I. Each of these individual cost penalties is small but each is a reasonable estimate of the intervening costs associated with a process to combine the two fuels into one liquid fuel. Without a wide difference in coal and fuel oil costs, the rationale of blending a cheap fuel with a more

## Table I. COLLOIDAL FUEL COST ESTIMATE (1974 DOLLARS)

| Step | Parameter | United | Baseline Case Value | Baseline Case Weighted % of Total Cost (Step 12) | | East Coast Case Value | East Coast Case Weighted % of Total Cost (Step 12) | |
|---|---|---|---|---|---|---|---|---|
| 1 | Coal/Blend weight ratio | – | 0.40 | – | | 0.40 | – | |
| 2 | Cost of Coal | $/ton | 11.27 | | 7.60 | 24.17 | | 14.99 |
| 3 | Coal Grinding Energy | Kwh/ton | 150 | | – | 150 | | – |
| 4 | Coal Grinding Cost | $/ton | 4.5 | | 3.03 | 4.5 | | 2.79 |
| 5 | Fixed Grinding Cost | $/ton | 0.87 | | 59 | 0.86 | | .54 |
| 6 | Coal Processing Cost | $/ton | 16.64 | 11.22 | 11.22 | 29.54 | 18.32 | 18.32 |
| 7 | Residual Fuel & Blending Cost | $/ton | 79.16 | | 80.07 | 79.16 | | 73.66 |
| 8 | Fixed Blending Cost | $/ton | 0.28 | | .28 | 0.28 | | .26 |
| 9 | Oil Processing Cost | $/ton | 79.44 | 80.35 | 80.35 | 79.44 | 73.92 | 73.92 |
| 10 | Basic Cost of Colloidal Blend | $/ton | 54.32 | 91.57 | | 59.48 | 92.25 | |
| 11 | Colloidal Plant Operating Cost | $/ton | 5.00 | 8.43 | | 5.00 | 7.76 | |
| 12 | Total Colloidal Fuel Cost | $/ton | 59.32 | 100.00 | | 64.48 | 100.00 | |
| 13 | Colloidal Cost/M Btu | $/M Btu | 1.7478 | | | 1.8998 | | |
| 14 | Residual Fuel Oil Cost/ M Btu | $/M Btu | 1.9677 | 100.00 | | 1.9677 | 100.00 | |
| 15 | Residual-Colloidal Fuel Cost Difference | $/M Btu | 0.2199 | 11.17 | | 0.0679 | 3.45 | |

NOTES:

Step 7 – Residual Fuel Oil Cost = $12.20/bbl (July 1974 national avg.)
Step 12 – 40% coal in mixture produces 33.94 M Btu/ton
Step 14 & 15 – Percent entered is per residual cost

expensive fuel can result in marginal savings only. As a rule of thumb, the cost of coal per ton would have to be considerably less than the cost of fuel oil per barrel if a colloidal fuel is to provide significant fuel savings for a given energy demand. Unfortunately, recent trends indicate that the price of coal will be paced by the prevailing price of petroleum fuels. Since the current cost differential of the two fuels will not result in an attractively economical colloidal fuel substitute for the residual fuels, a significant cost differential between the two fuels may never develop as the cost of petroleum fuels increases.

Although this analysis concludes that colloidal fuels may never be economically attractive competitors to the residual fuels, colloidal fuels should not be more expensive than the residual fuels. The primary value of colloidal fuels may be in providing a means of extending domestic petroleum fuel stocks in the event of another embargo by OPEC (Organization of Petroleum Exporting Countries). Solving the technical problems associated with converting residual fuel burning boilers to using colloidal fuels should not be postponed to the time that an emergency may demand the usability of the alternative fuels. No significant testing of colloidal fuels in boilers has occurred since 1943. **Therefore, full scale testing** of colloidal fuels in modern boilers would be constructive in expediting the use of a readily employable contingency fuel for a future emergency.

Technology Assessment

Coal in oil slurries received considerable attention in World War I and World War II. Coal slurries were used as fuels on an experimental basis by the British in 1932 on the Cunard Steamship liner "Scythia" with further testing shortly afterwards on another liner, the "Berengaria." Related testing of "Fliesskohle" (flowing coal or coal slurries) were conducted in Germany at approximately the same time (References 1 and 5). Results of these tests were poorly reported because the tests were for the purpose of determining a fallback fuels position in the event that fuel oil supplies became limited in wartime. Coal slurries were used successfully in a diesel engine in 1936. However, the low cost of fuel oil at the time rendered coal slurries unattractive as fuels for diesels (Reference 1).

Colloidal mixtures normally utilize residual fuel oils such as No. 6 or Bunker C as the basic solvent for the coal additive. Residual fuels may have a typical ash content of 0.01 to 0.5 percent by weight, a sulfur content of 0.7 to 3.5 percent by weight and a vanadium and nickel content of 10 to 500 parts per million (Reference 3). Bunker C has a higher heating value (HHV) of 18,000 Btu/lb. However, the actual physical characteristics of Bunker C can vary considerably and the quality of residual fuel oils depends on many refining factors. Essentially, the quality of residual oils is decreasing as the refineries produce greater quantities of the lighter products.

Residual fuels, including Bunker C must be preheated to 90° to 120°F to reduce their viscosity for handling. The fuel is then further heated to 165° to 200°F to reduce the viscosity further for proper atomization in burners (Reference 3).

Coal slurries using coal crushed to sizes of 200 mesh particles to 4 micron powders have been tested. The larger coal particles have been mixed with heavy fuel oils and the smaller coal powders have been mixed with diesel oil (Reference 1). The slurries using larger coal particles may require agitation to maintain particle suspension depending on the density of the oil. Mixtures having up to 50 percent coal by weight are feasible. Higher coal fractions are desirable but are beyond normal pumping methods. The maximum practical coal content for colloidal fuels is usually 40% by weight.

Table II is a tabulation of some selected physical characteristics of colloidal fuels from test data on a No. 6 residual oil blended with two different coal batches. The sulfur content of the tested coals is relatively low. The cost of coal with 1% sulfur is $10 per ton higher than coal with 2.25% sulfur at approximately $28 per ton (Appendix D). The low sulfur coals of Table II would obviously contribute to more expensive colloidal fuel products.

Sulfur in coal is in three forms; pyritic sulfur, which is sulfur combined with iron in the form of mineral pyrite or marcasite; organic sulfur, which chemically combined with the coal; and sulfate sulfur, which is in the form calcium sulfate or iron sulfate. Sulfate sulfur content in coal is usually much less than 0.1% and consequently does not present significant problems. Pyritic sulfur can be partially removed using standard coal washing techniques but the degree of removal depends on the size of the coal and the size of the pyrite particles. Because organic sulfur is chemically bonded to the coal, it is usually considered

## Table II A COMPARISON OF SELECTED FUEL CHARACTERISTICS

| Characteristics | #6 Fuel Oil | Coal Batch #1 | Coal Batch #2 | Colloidal Fuel Batch #1 | Colloidal Fuel Batch #2 | #2 Heating Diesel Oil | #2 Heating Diesel (#2) | JP-5 | General GT Fuel* | Gasoline |
|---|---|---|---|---|---|---|---|---|---|---|
| Coal, % by wt. | – | – | – | 39.4 | 33.7 | – | – | – | – | – |
| Sulfur, % by wt. | 1.5 | 0.8 | 0.8 | 1.3 | 1.4 | 1.0 | 1.0 | 0.4 | 1.3 | 0.3 |
| Ash, % by wt. | 0.1 | 6.1 | 7.8 | 2.4 | 3.1 | 0.0 | 0.02 | – | 0.01 | 0.01 |
| Vn & Ni, ppm | 10-500 | – | – | 6-300 | 6-300 | 6-300 | – | – | 0.5 | 0.5 |
| Specific Gravity | 0.98 | – | – | 1.032 | 1.094 | 0.865 | (0.89) | (0.845) | (~0.845) | (0.76) |
| Btu/1bm | 18,320 | 14,310 | 13,990 | 16,820 | 16,670 | 19,430 | (20,000) | ~20,000 | (~20,000) | 20,750 |
| Viscosity in secs: | | | | | | | | | | |
| SF @ 100°F | 128.7 | – | – | 642 | 1015 | ~1.39** | | | | |
| C @ 100°F | 278 | – | – | 1387 | 2192 | (3.0) | (5.8) | ~2.5 | (~2.5) | ~0.6 |
| SF @ 170°F | 17.0 | – | – | 73 | 107 | | | | | |
| C @ 170°F | 40.2 | – | – | 153 | 231 | | | | | |

SF = Saybolt Furol - used for heavy oils
C = Centistokes

*Based on the general fuel specification for the marinized, aircraft type LM2500 gas turbine used by the U.S. Navy and industrial power plants.

**The SF value for #2 Heating Oil is calculated for reference and does not reflect a tested value.

Values in parentheses are maximum limits.

~ is used to indicate an approximated or calculated value.

an inherent and non-removable impurity in coal. Organic sulfur may comprise 20 to 80% of the total sulfur content in the coal (Reference 3). Centrifugal separators have been designed to eject the heavy ash and pyrite particles from pulverized coal. Assuming a 100% separation efficiency, all of the ash and all of the pyritic sulfur could be mechanically removed from the feed coal. However, the organic sulfur would not be removed by this centrifugal separation. The percent of organic sulfur in coal is not usually specified in coal analyses; however, a reasonable assumption is that organic sulfur represents 50% of the total sulfur in coal, based on the median relative content of organic sulfur. An "economical" coal containing 2.25% sulfur would then retain at least 1.125% organic sulfur after a mechanical (centrifugal) separation process. The sulfur content of the coal batches in Table II consequently reflect an optimistically low sulfur product that might result from an efficient mechanical separator. The low sulfur content in the coal of Table II results in relatively low sulfur colloidal fuel batches. Realistically, the sulfur content in a colloidal fuel should be at least the proportion in the residual fuel component.

The ash content of the coal batches in Table II are also low but can be considered to be the proportion of ash which would remain after a conventional washing process. However, the resultant ash levels in the colloidal blends are high for fuel oil burning boilers which will foul from high ash levels. Mechanical separation may be able to remove a considerable proportion of the ash in coal after the washing process. However, the ash content in residual fuel oil is in the order of 0.1% or less. Over 99% of the ash in washed coal would have to be removed to reach the low ash levels of the residual fuel oil. Realistically, approximately 50% of the ash in washed

coal may be removed by mechanical separation. Colloidal fuel produced from this product will have at least 12 to 15 times the ash content of residual fuel oil.

Colloidal fuels are somewhat more viscous than residual fuels particularly as coal particle sizes are reduced less than 70 microns. Note in Table II that the impact of the finer coal of Batch #2 results in a more viscous colloidal fuel than that of Batch #1. Fuel pumping power requirements will increase as a consequence of the increased viscosity and normal preheating temperatures may have to be increased 15$^{\circ}$ to 50$^{\circ}$F to reduce the viscosity of the colloidal fuel to a manageable level. However, these are minor technical problems compared to the boiler fouling effects from the ash content in the colloidal fuel. Regular soot blowing of the boiler tubes has been used to reduce fly-ash fouling effects successfully. Most testing of colloidal fuels in actual boiler operation occurred over 30 years ago (Reference 7). Renewed testing of colloidal fuels on modern boilers would be necessary to determine the deleterious effects of slag build-up and other ash fouling problems with modern boilers. Possibly, some types of boilers could be relatively easy to convert to colloidal fuels with a minimum of ash fouling effects.

The conversion of residual fuel burning boilers to colloidal fuels may not be a straightforward process. Much new testing of colloidal fuels in actual boiler installations would be necessary to establish the limits to boiler convertability to the colloidal fuels. Even with the most optimistic estimates of sulfur and ash removal, the sulfur and particulate emissions from burning colloidal fuel may be considerably higher than those from burning residual fuels.

The environmental impact of the colloidal fuel alternative appears to be more detrimental than the effects of conventional fuels. Relaxed emission restrictions or stack scrubbing equipment, as coal burning plants would use, would be prerequisite to substituting colloidal fuels for residual fuels in appropriate steam plants.

Table II also indicates the specified limits of selected critical properties for the lighter fuels to illustrate the degree of disparity between colloidal fuel properties and the lighter fuel products. The sulfur limits on the various lighter fuels are mostly related to corrosive effects to machinery, rather than to pollution limits. However, the sulfur limits are not stringent compared to the ash limits. Gas turbine fuel and gasoline are particularly intolerant of ash and of vanadium and nickel content. Actually, the overriding characteristics which would limit colloidal fuels from being used in lieu of the lighter fuels is the viscosity limits of the lighter fuels.

## Current Efforts in Colloidal Fuel Usage

The recent energy crisis has brought about new interest in coal slurries. The Babcock and Wilcox Company is currently conducting laboratory scale tests to study the possibility of using coal slurry fuels for steam boilers (Reference 6). Coal slurries offer the primary advantage of extending the availability of petroleum based fuel oils via the coal additive. However, coal slurries pose certain serious disadvantages. The coal in the fuel tends to increase the combustion flame envelope; consequently, coal slurries generally require more volume than oil-fired boilers require. Coal tends to have a high proportion of ash at 6 to 11 percent by weight which is diffi-

cult to remove and which tends to cause boiler fouling problems. The sulfur content in bituminous coal can vary from 0.7 to 4 percent by weight. The heating value of coal can vary from 12,000 Btu/lb to 15,300 Btu/lb for bituminous and anthracite coals to much less than 12,000 Btu/lb for the subbituminous and lignite coals.

A "thermal shock splitting" process which has been proposed by the ILOK Powder Company of Washington, D. C., (Reference 1) may reduce coal particles to the submicron size claimed. However, this is still a mechanical process and would not chemically unbind the organic sulfur from the coal even if it could further separate ash and pyritic sulfur from micron size coal. Consequently, nothing in the proposed ILOK coal submicron reduction process (also known as the "Rohrback" process for the German inventor) which would eliminate the organic sulfur content of the coal is apparent.

ILOK proposes to blend submicron coal with the lighter fuels to provide colloidal substitutes for the lighter fuels. However, the submicron coal would definitely increase the viscosity of the lighter fuels in a manner similar to the way the micron size coal increases the viscosity of the residual oil as indicated in Table II. The degree of viscosity increase will be more dramatic from blending submicron coal to the lighter fuels. Machinery such as diesels, turbines and gasoline powered engines are not designed for the higher viscosities. These kind of engines would tend to gum-up from sludge remaining from the incomplete combustion of the "light" colloidal fuels. Although a diesel engine was successfully operated on a colloidal fuel in 1936, there is no technological basis for the ILOK assumption that colloidal fuels may be directly substituted for the light fuels in a general manner. Industrial gas turbines are presently being developed to burn the dirtier residual fuels; however, this development

is no basis for assuming that aircraft gas turbines could be adapted to burn colloidal fuels. To include a fuel pre-heating system to reduce the viscosity of the colloidal fuel in a jet aircraft may be a technological challenge in itself.

General Motors (GM) has successfully tested coal-oil mixtures in a power station at one of their manufacturing facilities in Saginaw, Michigan. Plant scale pilot tests were initiated in August, 1974. Coal reduced to 74 micron was blended 30 to 40 percent by weight with residual fuel oils and burned in their oil-fired boilers. Initial test results were encouraging. The adverse effects of burning a coal-oil mixture in an oil-fired industrial boiler appeared to be minimal for the limited duration of the pilot tests. Although a special type of pump was used to pump the coal-oil mixture, the standard fuel oil burner gun was not replaced. GM indicated that their major technical problems were in the storage and handling of the coal suspension.

The coal had to be resuspended by vigorous agitation and stirring. High particulate omissions resulted from the high ash content of coal (compared to that of fuel oil). However, GM determined through emission tests that particulate emission from medium and high ash coal could be removed relatively efficiently with conventional particulate collectors.

In future testing, GM plans to vary boiler combustion conditions to maximize thermal efficiency yet minimize particulate emission; test several types of coals and determine their impact on boiler hardware; to use higher weight proportions of coal, and to test the use of a fuel additive which will stabilize the suspension of the coal particles in the fuel oil.

The approach of using a thixatropic additive to maintain the stability of the colloidal suspension is attractive. Little or no agitation to maintain the suspension would be required; consequently, conventional storage systems would not require modification for special agitation systems. This feature would expedite the near-term convertibility to colloidal fuels and the relatively direct use of coal to offset some portion of domestic residual fuel requirements. If the thixatropic additive can be employed successfully, coal would not have to be reduced below 74 microns to produce a stable colloidal mixture. Therefore, the energy and expense related to crushing coal to submicron particle size as is normally required for colloidal fuels may not be necessary with the thixatropic additive.

The main objective of the current GM effort is to demonstrate that a coal-oil mixture with 32% coal (by weight) can provide 25% of the heat value of the coal-oil mixture. An ultimate goal is to demonstrate that a 50% mixture is feasible which would cut fuel oil usage by 41% per Btu required. The GM program of tests of colloidal fuels in modern boilers is probably the most significant colloidal fuel test program since the 1940s.

## Potential DOD Use of Colloidal Fuels

The only realistic potential application area for colloidal fuels is the residual fuel market. Bureau of Mines data (Reference 8) indicates that 19.35 million barrels of residual fuel oil was sold to all military users in 1973. The total energy required in residual oil would then be $120 \times 10^{12}$ Btu for 1973. If 1974 energy requirements were based on a 10% growth of 1973 energy requirements (hypothetical assumption

since military energy consumption actually decreased for 1974), 1974 energy requirements would be $132 \times 10^{12}$ million Btu. This is one tenth of the total DOD energy requirements projected for 1974 as reported by BCL. Only one tenth of the total energy DOD use can be identified as the residual fuel oil contribution. If a residual fuel cost reduction of $0.218/million Btu could be achieved with a colloidal fuel as indicated on Table I, a hypothetical 1974 fuel savings of $29 million could be projected. This degree of savings would not pay for one half the construction of a prototype coal powder plant. The main point is, however, that this is an upper limit number and that the degree of savings may be much less than $29 million per year (in 1974 dollars). The savings margin could be much lower. Operating expenses could inflate faster than the cost difference between coal and residual oil resulting in a net loss margin for any number of years.

The following Figures 1, 2 and 3 and Tables III, IV and V are taken from a study conducted for the Assistant Secretary of Defense (Installations & Logistics) in November 1973 (Reference 13). Department of Defense (DOD) use of various fuels is projected for 1974 in this study. Figure 1 illustrates that the DOD would require an estimated 2.4% of the total U.S. energy requirement for 1974. Of that total energy requirement, 72.5% would be of petroleum origin. Figure 2 illustrates the 1974 projected DOD petroleum demand compared to the total U.S. demand and the proportional petroleum demand by each service. Also noted on Figure 2 is that 50% of the petroleum use is provided by foreign suppliers and that the Air Force is the largest DOD user of petroleum fuels. Figure 3 indicates that, of the various military

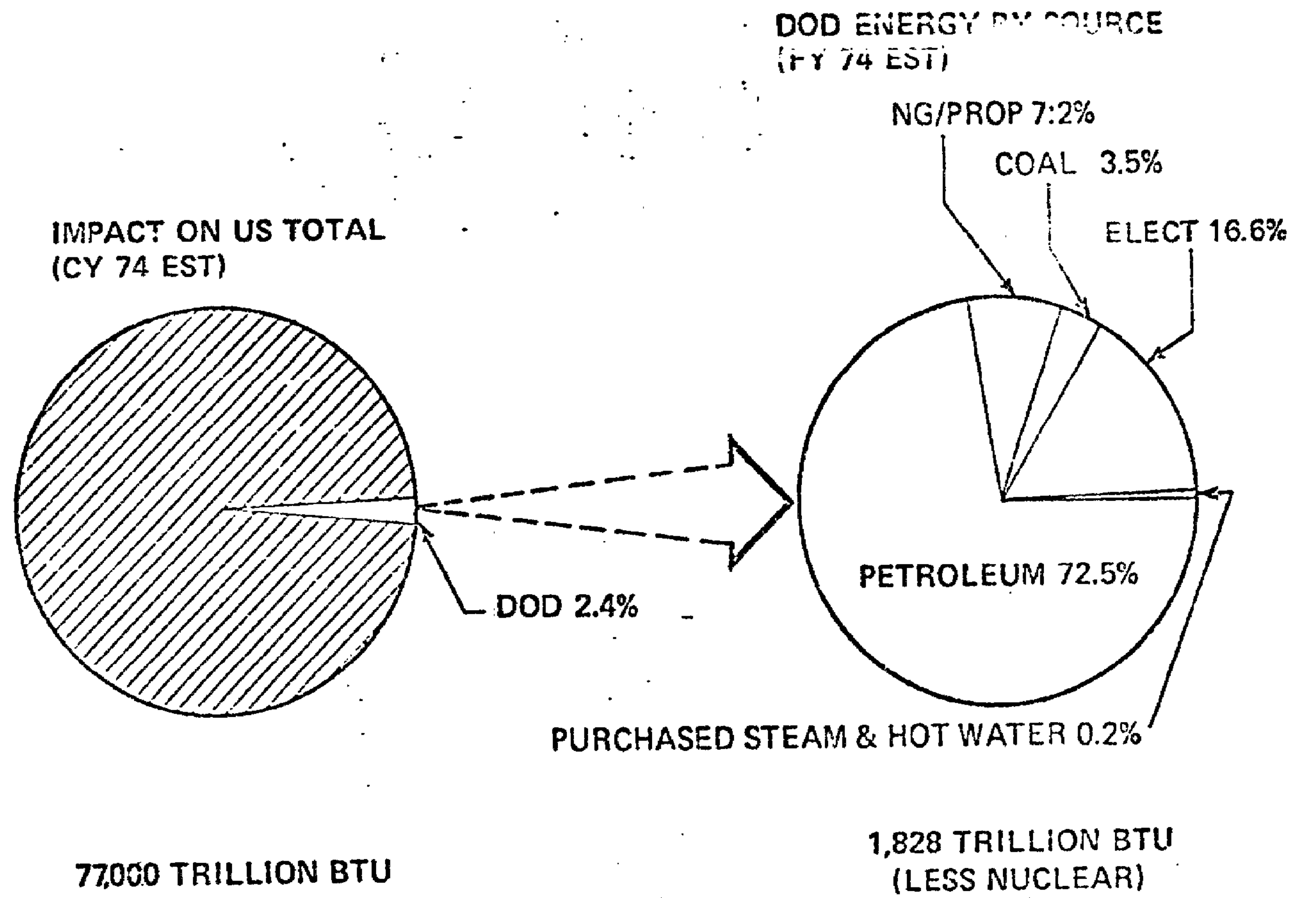



FIGURE 1. TOTAL DOD ENERGY (EXCLUDING NUCLEAR)

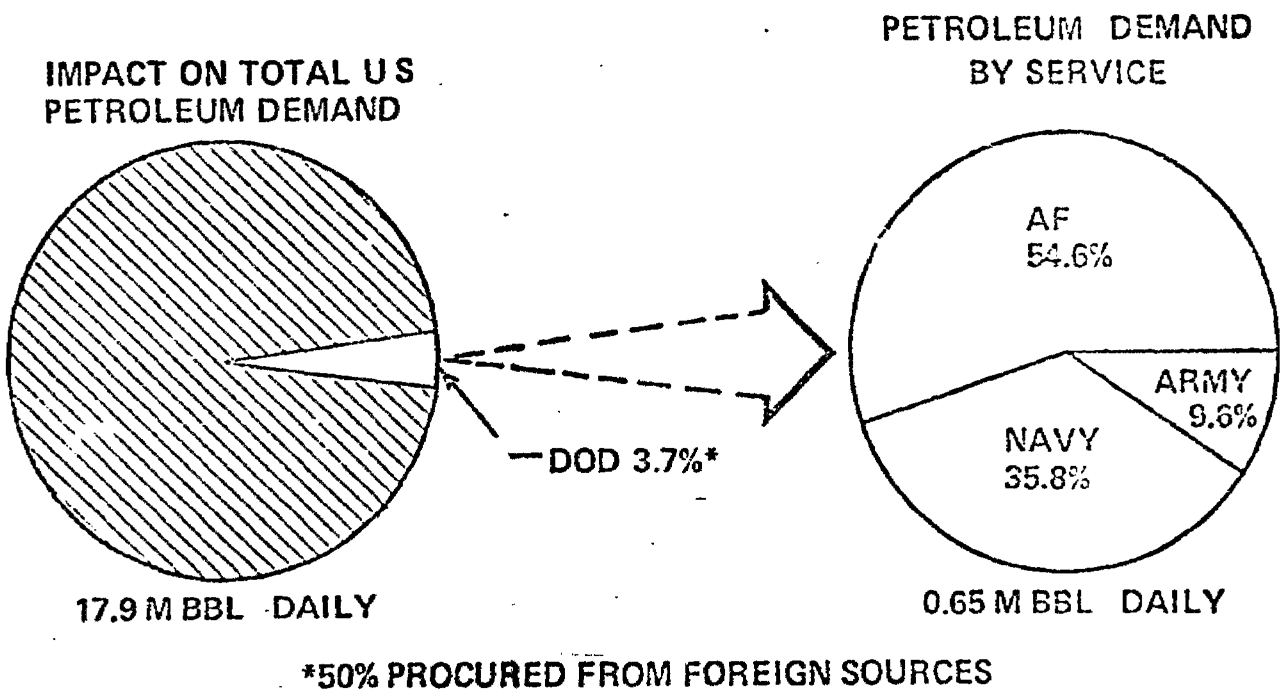



FIGURE 2. ESTIMATED TOTAL FY74 DOD PETROLEUM ENERGY DEMAND

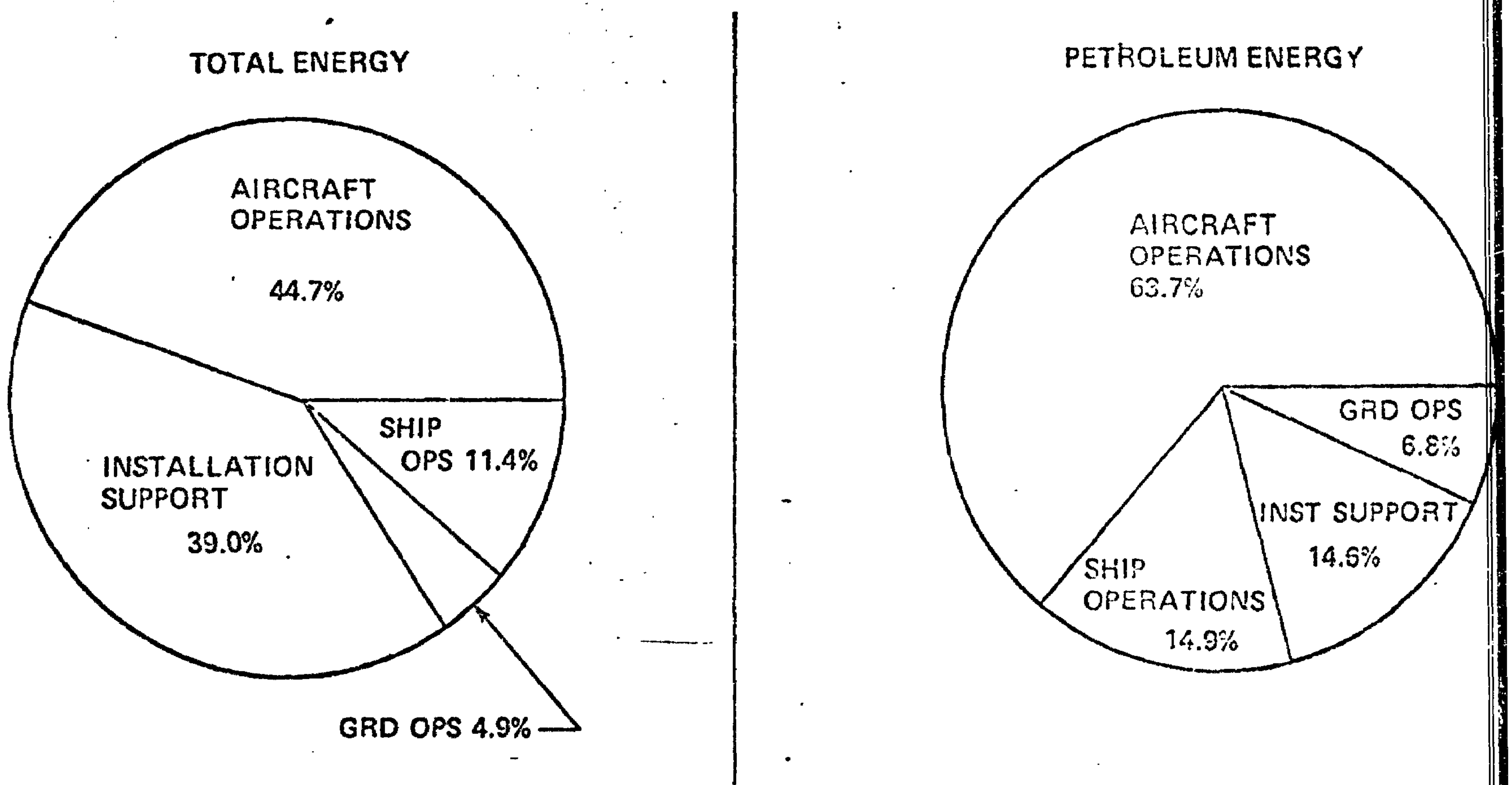



FIGURE 3. ESTIMATED FY74 DOD ENERGY DEMAND (BY OPERATIONAL FUNCTION)

TABLE III

## ESTIMATED ENERGY CONSUMPTION BY TYPE OF USE IN FY74, EXCLUDING NUCLEAR
(Trillions of Btu)

| Use | Army | Navy | Air Force | Total | Percent of DoD |
|---|---|---|---|---|---|
| Aircraft Operations | 20 | 174 | 623 | 817 | 44.7 |
| Ship Operations | * | 209 | — | 209 | 11.4 |
| Ground Operations | 43 | 23 | 23 | 89 | 4.9 |
| Installation Support | 258 | 221 | 234 | 713 | 39.0 |
| Total | 321 | 627 | 880 | 1,828 | — |
| Percent of DoD Consumption | 17.6 | 34.3 | 48.1 | — | 100.0 |

*Minor amount, included in ground operations.

TABLE IV

## ESTIMATED CONSUMPTION OF PETROLEUM FUELS BY TYPE OF USE IN FY74
(Thousands of Barrels)

| Use | Army | Navy | Air Force | Total | Percent of DoD |
|---|---|---|---|---|---|
| Aircraft Operations | | | | | |
| AvGas | 545 | 2,004 | 4,207 | 6,756 | |
| Jet | 3,094 | 29,229 | 112,669 | 144,992 | |
| | 3,639 | 31,233 | 116,876 | 151,748 | 63.7 |
| Ship Operations | * | 35,456 | - | 35,456 | 14.9 |
| Ground Operations | 7,753 | 4,050 | 4,291 | 16,094 | 6.8 |
| Installation Support (petroleum only) | 11,365 | 14,565 | 8,722 | 34,652 | 14.6 |
| Total | 22,757 | 85,304 | 129,889 | 237,950 | |
| Percent of DoD Consumption | 9.6 | 35.8 | 54.6 | | 100.0 |

* Minor amount, included in ground operations

## TABLE V

### ESTIMATED ENERGY CONSUMPTION IN FY74. EXCLUDING NUCLEAR

| Type of Energy | Army | Navy | Air Force | Total |
|---|---|---|---|---|
| **Petroleum (thousands of barrels)** | | | | |
| AvGas | 545 | 2,004 | 4,207 | 6,756 |
| Jet Fuel | 3,094 | 31,140 | 112,669 | 146,903 |
| MoGas | 3,405 | 1,685 | 2,793 | 7,883 |
| Navy Special Fuel Oil (NSFO) | 350 | 11,035 | 500 | 11,885 |
| Navy Distillate Fuel Oil (NDFO) | — | 23,912 | — | 23,912 |
| Residuals (less NSFO) | 3,324 | 7,268 | 2,231 | 12,823 |
| Distillates (less NDFO) | 12,039 | 8,274 | 7,489 | 27,802 |
| Total | 22,757 | 85,318 | 129,889 | 237,964 |
| **Natural Gas/Propane (millions of cubic feet)** | 49,281 | 29,760 | 42,000 | 121,041 |
| **Coal (tons)** | 1,928,000 | 150,277 | 550,000 | 2,628,277 |
| **Electricity (millions of watt hours)** | 7,950,000 | 8,090,972 | 10,150,000 | 26,190,972 |
| **Purchased Steam and Hot Water (thousands of pounds)** | 616,000 | 1,065,698 | 725,000 | 2,406,698 |

functions, aircraft operations require the greatest portion of the total DOD energy requirement. Aircraft operations require nearly 2/3 of the total petroleum energy requirement in DOD. Aircraft require the lighter, more precisely refined and therefore, the more expensive petroleum fuels. Tables III and IV are general breakdowns of how each service would allocate energy to their various operations. Table V is a breakdown of how various categories of petroleum fuels and other energy sources (excluding nuclear) would be used in 1974. Table VI is derived from the quantities of each fuel type to have been used by DOD in 1974 and unit cost figures for each fuel. The unit cost figures are not actually uniformly determined since price and cost averages for 1974 are yet to be established. However, the unit costs given do reflect the relatively lower costs of the lower grade fuels. The given unit costs are used to generate the nominal budget DOD would require for each general grade of fuel. For purposes of simplification, NDFO is lumped-in with other distillate fuels and NSFO is lumped-in with other residual fuels. The cost of coal and electricity are included on this table as incidental information.

As indicated in the "Technology Assessment" section of this report, colloidal fuels could be a potential substitute for the residual fuels only. Table VI indicates that DOD expenditures for residual fuels including those used by ships (NSFO) would be less than 9% of the DOD petroleum fuel budget. If the savings margin with colloidal fuels amounted to a 20% discount on the cost of residual fuels, a total DOD petroleum fuel budget savings of only 1.8% may be achievable with colloidal fuels. However, as indicated in the "Cost Assessment" of this report, the colloidal fuel savings margin could be considerably less than 10%. Consequently, no

## Table VI. RELATIVE COST OF VARIOUS GENERAL FUELS USED IN DOD

| Energy Type | Note | Total DOD Use for 1974 Estimated | Nominal Rate $ per Unit | Nominal Cost, $ per barrel | Total Estimated 1974 DOD Cost | % Cost |
|---|---|---|---|---|---|---|
| Petroleum (Million bbls) | | | | (42 gals) | $ Million | |
| AV Gas | 1 | 6.756 | 0.437/gal | 18.35 | 123.97 | 3.45 |
| Jet Fuel | 2 | 146.9 | 0.371/gal | 15.59 | 2290.17 | 63.57 |
| Mo Gas | 3 | 7.883 | 0.301/gal | 16.00 | 126.13 | 3.50 |
| Distillates | 4 | 51.714 | | 14.24 | 736.41 | 20.44 |
| Residuals | 5 | 24.703 | | 13.18 | 325.65 | 9.04 |
| Total Petroleum Fuels Cost | | | | | 3602.33 | 100.00 |
| Coal, (Million Tons) | 6 | 2.626 | 17.5/ton | | 45.98 | |
| Natural Gas/ Propane, (MCF) | 6 | 121,041 | 0.5134/CF $\times 10^3$ | | 62.14 | |
| Electricity (Kwh) | 7 | $26,191 \times 10^6$ | 0.040/Kwh | | 1047.64 | |

**NOTES:**

Except as indicated, entered nominal rates are based on October 1974 DFSC bulk rate prices.

1 Nominal rate applies to all AvGas grades.

2 87% of jet fuel used in 1973 was JP-4 (Reference 13). Nominal rate calculated based on a weighted average.

3 Nominal rate is based on regular and no-lead but applies to all MoGas grades. Premium at 39.4 ¢ /gal did not represent a significant portion of 1973 MoGas use.

4 Total use includes NDFO and nominal rate applies to al light diesel fuels.

5 As much NSFO is used as other residual fuels; nominal rate is an average.

6 Nominal rate is based on the July, 1974 national average cost of coal (assuming bituminous) and the national average cost of natural gas from the latest FEA data (Reference 2).

7 Nominal rate is approximated based on average U.S. commercial rates to January, 1974 (Reference 4).

measurable budget savings is likely from the substitution of colloidal fuels for all DOD residual fuel use. Also, unless colloidal fuels can be developed to substitute for the lighter fuels, the figures in Table V indicate that colloidal fuels substituting for residual fuels can account for no more than 10% of total DOD use of petroleum fuels. Of that 10%, coal would contribute less than 40% of the energy (because the coal in the colloidal fuel is 40% by weight and the heating value of coal is less than that of the residual fuel oil component). Therefore, coal would offset less than 4% of the quantity of DOD petroleum fuel energy requirements. The coal in the colloidal fuels would not offset DOD petroleum energy needs to any significant extent and it would be much less significant when compared to total DOD energy requirements.

# APPENDIX A

## THE BCL COLLOIDAL FUEL COSTING RATIONALE

Table A is a breakdown of the step by step procedure used by BCL to estimate the cost of colloidal fuels in their report of Reference 1. The given input values (indicated by *) were selected only to collaborate BCL given input values with output results. The result values indicated in steps 14, 15, 16, 18 and 19 of Table A correlate perfectly to the number of significant digits with the appropriate computed results of the BCL parametric analysis (refer to page 24 of Ref. 1). Consequently, the methodology presented in Table A for calculating colloidal fuel costs accurately represents the BCL rationale.

Note that the blending equations are based on the Coal/Blend Ratio wh. ı is derived from and is much smaller than the Coal/Oil Ratio. A Coal/Oil Ratio of 0.70 would result in a Coal/Blend Ratio of 0.412 which is at the practical viscosity limit of pumpable slurry mixtures (Refs. 5, 6 and 7). BCL indicates that a Coal/Oil Ratio of 0.70 is "an improbably high value" (page 29 of Ref. 1). However, slurry fuel technology indicates that the coal proportion in a blend should be in the order of 40% to maximize the coal constituent within a pumpable fluid viscosity. A Coal/Oil Ratio as defined by BCL of up to 0.70 should not be considered an extremely high value.

Note that step 4 is the expected coal grinding energy requirement. BCL indicates that grinding energy could range from 25 to 250 kwh per ton. This is a very broad range and BCL provides no guidance as to the

## Table A. THE BCL COLLOIDAL FUEL COST ESTIMATION METHODOLOGY

| STEP | PARAMETER | EQUIVALENCIES | RESULTS | UNITS |
|---|---|---|---|---|
| 1 | Coal/Oil Weight Ratio | W * | 0.50 | |
| 2 | Coal/Blend Weight Ratio | $R = \frac{W}{1-W}$ | 0.333 | |
| 3 | Cost of Coal | $C_1$ * | 25.00 | $/ton |
| 4 | Coal Grinding Energy | G * | 25.0 | Kwh/ton |
| 5 | Electric Energy Cost | Ce * | 0.06 | $/Kwh |
| 6 | Coal Grinding Cost | $C_2 = G \times Ce$ | 1.5 | $/ton |
| 7 | Fixed Grinding Cost | $C_3$ | 3.00 | $/ton |
| 8 | Total Coal Processing Cost | $C_T = C_1+C_2+C_3$ | 29.5 | $/ton |
| 9 | Cost of (Residual Fuel) Oil | $F_1$ * | 15.00 | $/bbl |
| 10 | Blending Cost (Per Barrel of Oil) | $F_2$ * | 0.003 | $/bbl |
| 11 | Total Oil Processing Cost | $F_T = F_1 + F_2$ | 15.003 | $/bbl |
| 12 | Total Oil Processing Cost | $S = RC_T + (1-R)\,F_T$ | 74.11 | $/ton |
| 13 | Heating Value of Colloidal Blend | $H_s = RH_C + (R-1)H_F$ | 33.94 | M Btu/ton |
| 14 | Colloidal Cost Per Energy Unit | $Us = S/Hs$ | 2.183 | $/M Btu |
| 15 | Residual Fuel Cost Per E.U. | $U_F = F_1/H_F$ | 2.419 | $/M Btu |
| 16 | Colloidal Cost Savings Per E. U. | $Un = U_F - Us$ | 0.236 | $/M Btu |
| 17 | Per Cent Colloidal Savings | $P = Un/U_F$ | 9.77 | % |
| 18 | "Total Air Force Jet Fuel Savings" | $Un \times B_{AF}$ | 141.6 | $M/Yr |
| 19 | "Total DOD Fuel Savings" | $Un \times B_{DOD}$ | 312.7 | $M/Yr |

Notes: * - Selected input from BCL parameters.

Step 11, 12 & 13; $\frac{\text{Quantity}}{\text{bbl}} \times \frac{1}{\frac{325\text{ lb}}{\text{bbl}}} \times \frac{2000\text{ lb}}{\text{ton}} = \frac{\text{Quantity}}{\text{ton}}$

Step 13 & 15; $Hc = 25.5$ M Btu/ton, $H_F = 6.2$M Btu/bbl, M Btu = Btu$\times 10^6$

Step 18 & 19; $B_{AF} = 600 \times 10^6$M Btu, $B_{DOD} = 1{,}325 \times 10^6$M Btu; the BCL estimated Air Force and DOD total energy requirements for 1974 respectively.

most probable value that should be selected for grinding energy. BCL does indicate by their own analysis that the special mill to be used in the ILOK process will require in the order of 110 kwh/ton for only one of the four grinder stages (page 16 of Ref. 1). This estimated energy requirement is based on the energy absorbed by acceleration of the coal particles to the peripheral speeds of the beater elements in the grinding machine. This energy estimate has been determined by BCL through simplifying assumptions. However, BCL also indicates that "Experience in this country and calculations using Rittingers Law indicate (that) a coal grinding energy of at least 250 kwh (would be required to grind one ton of coal) to 4 micron size" (page 21 of Ref. 1). The 4 micron size is the minimum size required for blending with oil (residual oil implied). Consequently, from their own given information, BCL indicates that the minimum energy required for grinding coal to the required particle size should be at least 110 kwh/ton. The coal processing schematic of the special ILOK process (Figure 1, page 13 of Ref. 1) indicates no special pretreatment of bunker coal. The special grinder is similar in configuration to a high speed, attrition type, pulverizer and other impact machines and should not perform significantly differently than these conventional grinders. Consequently, with no analytical basis or empirical test experience to support the ILOK claim that their special grinder would require one-tenth of conventional grinding energy requirements, Rittingers Law should be considered the most credible basis for estimating coal grinding energy. A somewhat detailed analysis of coal pulverizing and grinding energy is presented in Appendix B. The results of this analysis indicate that a coal grinding energy of 150 kwh/ton should be representative of the energy required to reduce coal to a 4 micron powder.

Note that step 5 is an electric energy cost of \$0.06 per kwh. BCL selects an electric cost range of \$0.02, \$0.04 and \$0.06 per kwh to parametrically vary the impact of electric rates on coal grinding costs. However, of all the varied parameters, the electric energy cost is probably the most stable cost. Electric energy rates for large volume users (industrial rates) were nearly constant and averaged slightly less than \$0.02 per kwh between 1960 and 1970. The average industrial electric rate increased from \$0.024 to \$0.028 per kwh between January 1, 1973 and January 1, 1974. Extending this trend linearly to January 1, 1975 indicates that an industrial rate of \$0.03 per kwh would be a reasonable estimate for the 1974 average rate.

Note that step 7 is an assumed fixed grinding cost of \$3.00 per ton of coal processed. This fixed cost should include the initial cost of borrowing the capital to purchase a basic coal powder plant. The ILOK Company, which is proposing the colloidal fuel as an alternative fuel, estimates that a coal powder plant of 10,000 tons per day would cost \$65 million (1972 dollars). If amortized over 30 years at 9%, this initial capital requirement would cost \$6.3 million per year in fixed cost expenses. At the annual production rate of 3.5 million tons based on 350 production days a year, the fixed production cost of the coal powder would be \$1.80 per ton (1972 dollars). This fixed cost represents the cost of raising the capital for the coal powder plant only. A fixed cost estimate of \$3.00 per ton appears to include a nominal margin for operating expenses, taxes, some profit margin and other non-fixed expenses.

## APPENDIX B

### Alternative Assessment of the Cost of Colloidal Fuels

The Battelle Columbus Laboratories (BCL) "Assessment of the Potential for Colloidal Fuels" (Reference 1) is essentially a parametric analysis of the range of fuel costs which could result from various coal and fuel oil compositions in colloidal fuel mixtures. However, in drafting conclusions, BCL indicates a maximum potential savings in energy costs to the Department of Defense (DOD) through the use of colloidal fuels based on the assumption that the coal component is relatively cheap per unit of energy compared to the petroleum component. BCL also assumes that the colloidal mixtures could be substituted for all the various fuels in use by DOD. The purpose of this "Alternative Assessment" is to bring the BCL parametrics into focus with the latest prices of coal and fuel oils using the same basic math model employed by BCL.

The BCL methodology for calculating the cost of colloidal fuel is not presented in their assessment report although the input and output values for their computerized methodology is presented. However, the BCL methodology can be determined from their reported analytical information. The correlation of the results from given input values for the determined BCL methodology is presented in Appendix A. Table I is a breakdown of the basic BCL methodology updated for current costs and revised to include other cost factors neglected by BCL. Refer to the basic terms and relationships indicated in Appendix A which are the bases of the calculations in Table I.

The assumptions and the rationale utilized in deriving Table I are described step by step below:

Step 1 - A 40% coal colloidal blend is used since this blend maximizes the quantity of coal that may be blended into the residual oil and not exceed the viscosity limits of a pumpable fluid (refer to Appendix A).

Step 2 - (Reference 2) The cost of coal is significantly higher in east coast locations than in other parts of the U.S. continent. Consequently, the Base Case reflects the average price of coal for the month of July, 1974 for the U.S. other than the east coast states. The East Coast Case reflects the average price for the same period for New England, Middle Atlantic and South Atlantic regions (FEA designations). The East Coast coal costs are nominally twice those for other regions in the country. The higher East Coast coal costs probably reflect the cost

## Table I. COLLOIDAL FUEL COST ESTIMATE (1974 DOLLARS)

| Step | Parameter | United | Baseline Case: Value | Baseline Case: Weighted % of Total Cost (Step 12) | | East Coast Case: Value | East Coast Case: Weighted % of Total Cost (Step 12) | |
|---|---|---|---|---|---|---|---|---|
| 1 | Coal/Blend weight ratio | – | 0.40 | – | | 0.40 | – | |
| 2 | Cost of Coal | S/ton | 11.27 | | 7.60 | 24.17 | | 14.99 |
| 3 | Coal Grinding Energy | Kwh/ton | 150 | | – | 150 | | – |
| 4 | Coal Grinding Cost | S/ton | 4.5 | | 3.03 | 4.5 | | 2.79 |
| 5 | Fixed Grinding Cost | S/ton | 0.87 | | 59 | 0.83 | | .54 |
| 6 | Coal Processing Cost | S/ton | 16.64 | 11.22 | 11.22 | 29.54 | 18.32 | 18.32 |
| 7 | Residual Fuel & Blending Cost | S/tcn | 79.16 | | 80.07 | 79.16 | | 73.66 |
| 8 | Fixed Blending Cost | S/ton | 0.23 | | .23 | 0.23 | | .26 |
| 9 | Oil F ocessing Cost | S/ton | 79.44 | 80.35 | 80.35 | 79.44 | 73.92 | 73.92 |
| 10 | Basic Cost of Colloidal Blend | S/ton | 54.32 | 91.57 | | 59.48 | 92.25 | |
| 11 | Colloidal Plant Operating Cost | S/ton | 5.00 | 8.43 | | 5.00 | 7.75 | |
| 12 | Total Colloidal Fuel Cost | S/ton | 59.32 | 100.00 | | 64.43 | 100.00 | |
| 13 | Colloidal Cost/M Btu | S/M Btu | 1.7478 | | | 1.8998 | | |
| 14 | Residual Fuel Oil Cost/ M Btu | S/M Btu | 1.9677 | 100.00 | | 1.9677 | 100.00 | |
| 15 | Residual-Colloidal Fuel Cost Difference | S/M Btu | 0.2199 | 11.17 | | 0.0679 | 3.45 | |

NOTES:

Step 7 — Residual Fuel Oil Cost = $12.20/bbl (July 1974 national avg.)

Step 12 — 40% coal in mixture produces 33.94 M Btu/ton

Step 14 & 15 — Percent entered is per residual cost

of transporting the coal. The national average cost of coal increased at a relatively constant rate over the first half of 1974. No national rate trends are available to indicate the average price of coal after July 1974. However, a recent publication by PEPCO (Potomac Electric Power Company of Washington, D.C.) indicates that the price of coal tended to stabilize for the second half of 1974 (refer to Appendix D). July should, therefore, represent the stabilized price of coal for 1974.

Step 3 - (Reference 3) The coal grinding energy is estimated here to be 150 Kwh/ton as developed in Appendix E.

Step 4 - (Reference 4) The coal grinding cost is based on the grinding energy and on the electric energy cost. The industrial electric rates were relatively constant at slightly less than 2 cents per Kwh between 1960 and 1970. However, the industrial rate has increased to approximately 2.75 cents per Kwh between 1970 and 1974. Based on the growth trends between 1973 and 1974, the average industrial rate for electric power should be 3 cents per Kwh. Note from the cost percentages for the Base Case in Table I that the coal grinding cost is a small factor in the overall cost of the colloidal fuel product. Consequently, the cost of the blended fuel product is relatively insensitive to the grinding energy requirements and the magnitude of the grinding energy should not be regarded as critical to the final product cost.

Step 5 - (Appendix C) The fixed cost for grinding the coal is based on the capital cost of the "Coal Powder Plant" indicated by ILOK, updated to 1974 capital costs, amortized over 30 years at a 9% corporate bond rate and determined per unit of blended fuel product (rather than per ton of coal input in the BCL approach).

Step 6 - The coal processing cost is simply the sum of the coal, grinding and capital costs per unit of product. Note that the capital cost of the "Coal Powder Plant" per unit of product is very small.

Step 7 - (Reference 2) Residual fuel costs have been relatively stable over the various national regions. The national average cost of residual fuel for the month of July 1974 is used to represent the stabilized cost for that year. Residual oil increased dramatically in the first month of 1974 but stabilized at approximately $12 per barrel for the following five months. Again, no national rate trends are available for the second half of 1974. The more recent fuel price trends published by PEPCO, however, do indicate that residual oil prices were stable for the last half of 1974 also (refer to Appendix D). Consequently, July should be a representative month for the stabilized price of residual for 1974. Step 7 sums the price of the residual oil at $12.20/bbl with the estimated blending cost of $0.663/bbl provided by BCL and this sum is then corrected for the common cost per unit weight in $/ton.

Step 8 - (Appendix C) The fixed blending cost is an estimate of the capital cost per unit of product of a blending plant which was not considered in the BCL Assessment. The cost of the blending plant is based on the cost of the most fundamental refinery process units. A blending plant should be equivalent in complexity to the simplest of refinery processes and since refinery cost statistics are available, the blending plant cost could be derived on a refinery technology basis. Note that the relative cost per unit of product of the blending plant capital cost is small.

Step 9 - The oil processing cost is merely the sum of the fuel cost (including blending cost) plus the fixed capital cost of a blending plant.

Step 10 - Refer to Appendix A for the basic blending formula which establishes a weighted unit cost of product based on the percent of each component to result in the final blend.

Step 11 - (Appendix C) A colloidal plant operating cost is included in cost breakdown although BCL does not include this factor. The cost of labor, maintenance, and miscellaneous facilities are a significant part of the cost of any finished product and should not be ignored. The operating cost is also based on refinery cost and operation experience. The process requiring the lowest operating cost in the refining process, topping, is the basis for estimating the overall operating cost of the "Colloidal Fuel Plant." A 1956 operating cost for a topping process, updated through the "Nelson Inflation Index" to 1974 is the basis for the given operating cost of $5 per ton of product. The operating cost is less than 10% of the product cost and should therefore be considered relatively credible. The operating cost does not include taxes or profit and this point is addressed later in the conclusions of this assessment.

Step 12 - The total colloidal fuel cost is the sum of the basic cost of the plant, the resources and the cost of operating the plant. Note that the colloidal fuel cost per unit weight is significantly less than the cost of the residual fuel for the same unit of weight (Step 7). However, the fuel blend will have a low heating value because of the much lower heating value of the coal component in the blend. Consequently, the final cost comparison must be made per unit of energy.

Step 13 - The colloidal fuel cost per unit of energy is derived from its cost per ton divided by its weighted average heating value per ton (33.94

million Btu/ton for a colloidal blend of 40% coal and 60% residual fuel oil). Refer to Appendix A for the blending effect on determining the weighted average heating value of the colloidal fuel.

Step 14 - The 1974 selected residual fuel oil cost at $12.20 per barrel is multiplied by a heating value of 6.2 million Btu/bbl to result in a cost per million Btu of $1.9677.

Step 15 - Subtracting the colloidal fuel cost from the residual fuel oil cost results in the potential savings per identical units of energy in using the colloidal fuel (unless the result is negative which would reveal a loss). As indicated in the percent column, the savings per energy unit using 1974 costs as a uniform basis could amount to 11% of the fuel costs of a system that could convert from residual fuel to a 40% coal colloidal fuel. The higher cost of coal for east coast users reduces the potential savings margin for using colloidal fuel to 3.45%

## Cost Assessment Conclusions

The savings margin achievable with a colloidal fuel is primarily sensitive to the cost differential of the raw materials, coal and residual oil, from which the colloidal fuel is made. This point is clearly deducible when comparing the savings margin of the Base Case to that of the East Coast Case with their respective coal costs since fuel oil costs are constant. From Table I, coal at $11.27 per ton is being blended with oil at $12.20 per barrel to result in a savings margin of 11%. As the cost of coal in the

East Coast case essentially doubles to \$24.17 per ton, the savings margin is reduced by as much as 2/3 to 3.45%. Where the price of coal per ton is identical to the price of residual fuel oil per barrel, the savings margin will be 10%. Reducing the cost of coal per ton to \$6.10, which is 1/2 the cost of residual fuel oil per barrel, would increase the savings margin to 14%. This order of savings begins to have significance. Consequently, the cost of residual oil would have to inflate at twice the rate of coal to generate the necessary cost differential. Without a wide difference in coal and fuel oil costs, the rationale of blending a cheap fuel with a more expensive one cannot result in significant savings. Therefore, as a rule of thumb, the cost of coal per ton must be less than 1/2 the cost of residual oil per barrel if a colloidal fuel is to provide significant fuel savings per unit of energy.

The 11% margin of the Base Case must cover taxes, profits, research, advertising and general administration expenses. If profits alone are to be only 7%, the savings margin will be less than 5% which may not have measurable significance. Distinguishing the impact of a fuel savings margin of less than 5% from plant efficiency fluctuations resulting from maintenance effects may be difficult. The given 11% savings margin is estimated using relatively optimistic cost factors in favor of the colloidal fuel manufacturing process.

## APPENDIX C

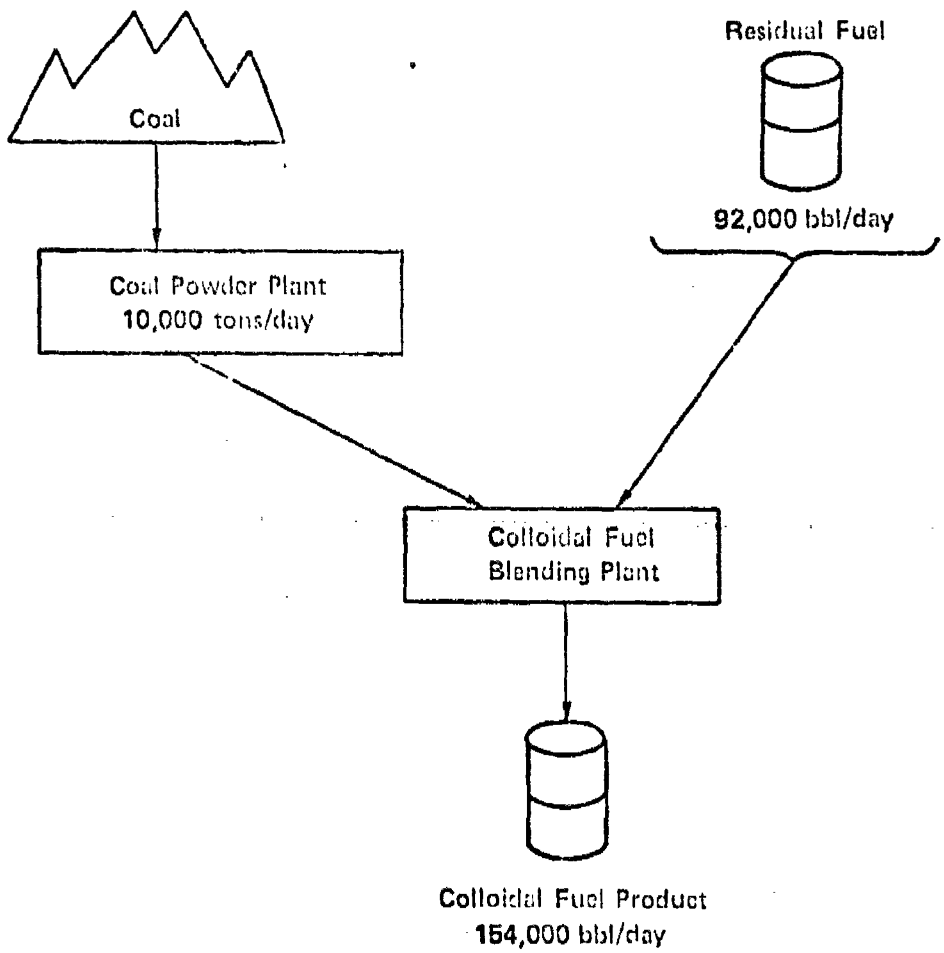
## COLLOIDAL FUEL BLENDING PLANT COST

The H-Oil Company, which is proposing to produce the colloidal fuel, estimates that the 10,000 tons/day Coal Powder Plant would cost \$65 million in 1972 dollars (Ref. 1, page 12). This capital cost would not apparently include the capital cost of the facilities required to blend the coal powder with the residual fuel oil which would result in a colloidal fuel product. The capital cost of a "Blending Plant" should be considered since large quantities of oil will be processed requiring large equipment, buildings, land and construction costs. If the colloidal fuel produced will be composed of 40% coal, then the 10,000 ton/day coal powder plant will require 15,000 tons/day of residual oil to produce the required colloidal product. In barrels, the oil required would be

$$\frac{15{,}000 \text{ tons}}{\text{day}} \times \frac{2{,}000 \text{ lbs}}{\text{ton}} \times \frac{1}{325 \text{ lbs/bbl}} = 92{,}308 \text{ bbl/day}$$

Since the specific gravity of the colloidal fuel product is nearly that of the residual fuel oil, the density of the colloidal fuel should be very similar to that of the residual oil. Therefore, the given Colloidal Fuel Blending Plant of Figure C would produce approximately 153,850 bbl/day of colloidal fuel. The capital cost of the blending plant may be based on the capital cost of petroleum refinery process units which are of a minimum of complexity. The petroleum industry has devised Nelson refinery cost indexing as an approach to generalizing the various costs involved in producing refinery products and to update or even projected inflated costs

Figure C. COLLOIDAL FUEL PLANT



(Ref. 10). A recent article using the Nelson approach indicated that the average 1973 construction cost of large process units (200,000 bbl/day) of the lowest levels of complexity would be $150 per barrel per day of production (Ref. 11). At a total production rate of 154,000 bbl/day, the simple blending process unit would cost $23 million to construct in 1973.

An index used to factor construction costs by the deflated value of the dollar is the "Nelson Inflation Index" (Ref. 11). Recently published Nelson Inflation Indexes indicate that the 1974 inflation rate was 10.5%. Consequently, the 1974 cost of the colloidal fuel plant would be $25 million. If a lending interest rate of 9% (Aaa Corporate Bonds, Ref. 12) could be obtained in 1974 for the construction of the plant, the cost of financing the plant over a thirty year period would result in an annual capital cost of $2.5 million. If the plant produces 350 days a year, the total annual production would be 54 million barrels. The capital cost per production unit would then be $0.046 per barrel or $0.28 per ton of product.

The Coal Powder Plant that cost $65 million in 1972 dollars would cost $78.7 million in 1974 dollars using the Nelson Inflation Indexes for 1973 and 1974. Through similar financing, the annual capital cost of the powder plant would be $7.65 million. The capital cost per production unit would then be $0.142 per barrel or $0.87 per ton of product.

The operating expenses for the colloidal fuel plant could also be based on petroleum industry operating cost. The base operating cost for the simplest refinery operation, topping, was estimated at $0.35/bbl for 1965. The Nelson Inflation Index applied to this base year results in an average 1974 operating cost of $0.812 per barrel of product ($5.00 per ton). This unit operating cost includes labor, maintenance, supervision,

royalties, and miscellaneous facilities. The unit operating cost does not include the cost of advertising, research, general administration, taxes or profits.

APPENDIX D

PEPCO FUEL COSTS

(Taken from a February 1974 publication of fuel prices for residential customers)

# /epco shops for the best price



Did you ever wonder much about the cost of coal? Probably not. Few Americans have reason to give it a thought since we pped burning it in the fireplace, years ago, to heat our homes.

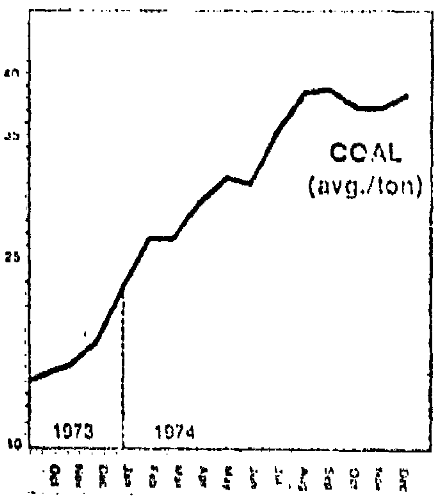
But today coal still comes into the house— n and powerful — and it's as much a part the budget as hamburger or dry cleaning or asoline.

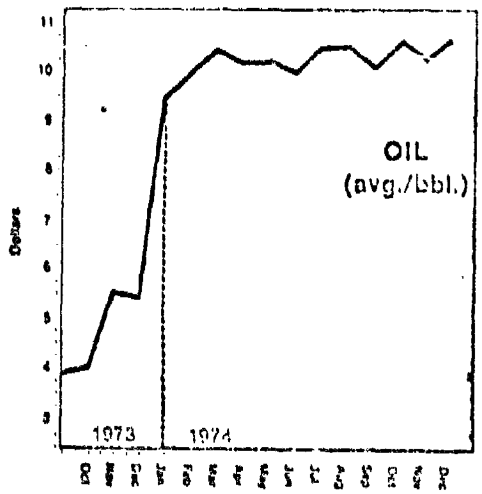
Today's coal is electricity. Burned in a con , controlled power plant, it heats the water roviding steam to the turbine-generators that nd out the electricity that gives us the highest standard of living in the world.

What about the cost? Electricity is not the taken-for-granted item it used to be, and the main reason is the rising cost of the two basic fuels used to generate it for your home or place of work.

Those fuels are oil and coal. Because of the actions of the oil producing nations, the price PEPCO pays for a barrel of oil rose from approximately \$3.86 to \$10.28 in the one-year period ending September, 1974, and it still fluctuates at above that level. Tripled, in a year!

(over)




# al cars roll to save money

ost of coal has risen at almost the ate! With demand for coal far ex- supply, the average price rose in the ar from about \$14.16 per ton to ap- ately \$37.87. Now the price is d to climb again as a result of the ke settlement.

s has meant higher bills for electricity ers everywhere, for reasons beyond y's control. But the increases have the same throughout the country. very electric company pays the same r ton for coal because many different ffect coal n different parts of n. These include the volume ed, the quality, the methods of g it to the power plants, freight rates, ance from the mines, and the mental constraints on its use.

O buys two different kinds of coal. In six months of 1974, for example, we ed approximately 1.55 million tons of cent sulfur content coal. Another ons were 1 percent sulfur coal. e 2.25 percent sulfur coal, in these six PEPCO paid an average price of er ton—which was midway in the ge (from \$15.53 to \$37.46) paid for e Middle Atlantic region. ost PEPCO more than it cost in rer the coal fields, but less per ton reas where transportation was a ost factor.

mental restrictions in the District of Columbia and Virginia require PEPCO to burn 1 percent sulfur coal. For this small portion of our coal, we paid an average of \$36.79 per ton in a scale ranging up to \$40.34 in the Middle Atlantic area.

So even with environmental requirements for PEPCO to burn this expensive grade of coal, we still do not pay top dollar for it in this region, or in the country.

As part of PEPCO's effort to keep coal costs down, we use the generating plants that require the 1 percent sulfur coal only when customer demands increase or when needed for system reliability.

As for PEPCO's oil prices, in those same six months of 1974 we had the lowest dollar-per-barrel average cost in the same Middle Atlantic region. PEPCO paid \$9.97 per barrel, while in adjoining states the price ranged from \$10.20 to \$13.29 per barrel.

PEPCO is doing many things to hold down the prices of its coal—including buying our own railroad cars to bring down cost.

LM2500 GAS TURBINE FUEL SPECIFICATIONS

(From General Electric Specification
MID-IDM-2500-2 of August 1972)

This document lists the specifications for liquid fuel that can be fired in the 7LM2500 Gas Turbine; in addition it lists additional characteristic and conditions not covered by these fuel specifications.

1. FUEL SPECIFICATIONS

Fuels meeting the following specifications are acceptable for use in the 7LM2500 gas turbine provided they meet the additional criteria listed in paragraph 2.

| | Specification No. | Title |
|---|---|---|
| 1.1 | MIL-T-5624G | Grades JP4, JP5 |
| 1.2 | ASTM D975-68 | Diesel Fuel Oil, Grades 1-D and 2-D |
| 1.3 | ASTM D1655-69 | Turbine Fuels |
| 1.4 | MIL-F-24397 | Fuel - Navy Distillate |
| 1.5 | MIL-F-16884F | Fuel Oil - Diesel Marine |
| 1.6 | VV-F-800A | Fuel Oil - Diesel, Grades DF-A, DF-1 & DF-2 |

2. ADDITIONAL REQUIREMENTS

The following requirements supplement and supersede, where there is a conflict, the specifications listed in paragraph 1.0. However, if the specification requirement is more restrictive it applies:

2.1 The fuel shall consist of hydro-carbon compounds only and shall be the distillate type containing no cracked material.

2.2 The use of any additives requires the approval of the General Electric Company.

2.3 The viscosity of the fuel as supplied to the inlet connection on the gas turbine shall be 6.0 centistokes or less. The fuel may be heated to meet this requirement.

2.4

| | |
|---|---|
| Ash, maximum percent | 0.01 |
| Sulfur, maximum percent | 1.3 |
| Vanadium, maximum, ppm | 0.5 |
| Sodium + Potassium, maximum ppm | 1.0 |
| Hydrogen Content, minimum % | 12.3 |
| Demulsification, minutes, maximum | 20.0 |

2.5 The fuel as delivered to the inlet connection on the gas turbine shall not contain more than 10 grams of solid contaminates per 1000 gallons of fuel. The contamination shall not exceed the following micron size limits:

| Particle Size, Microns | Percent of Total |
|---|---|
| 0-5 | Remainder |
| 5-10 | 18% Maximum |
| 10-20 | 16% Maximum |

2.6 The fuel as delivered to the inlet connection on the gas turbine shall not contain more than 10 ppm of entrained water at 70°F.

# APPENDIX E

## GRINDING ENERGY REQUIREMENTS

The work required for grinding coal is not easily derived from the general technology of pulverizing and grinding technology. Grinding energy estimation methods seem based more on "rule of thumb" equations than any well-developed discipline. One utilities equipment selection handbook recommends that the power required for pulverizing coal could be approximated at 1 kwh per ton (Ref. 9) although the size of the pulverized product is not actually specified (200 mesh; that is, 74 microns is normally required for coal burning boilers used by utilities). One engineering handbook (Ref. 3, pages 8-52) indicates that the crushing energy for anthracite coal is 246 to 330 kwh per ton to achieve a 6-7 micron particle size. Anthracite is much harder than bituminous coal and the crushing and grinding energy of the two materials is related to their Hargrove Grindability Indexes. Anthracite has a Hargrove Grindability Index of 20, whereas bituminous coals establish the Hargrove Grindability Index of 100. The magnitudes of these indexes indicate that anthracite coal is much harder to grind than bituminous coal. Consequently, the energy required to grind anthracite coal should not be the basis for establishing the average energy required to crush bituminous coals.

Grinding technology recognizes three general laws for relating particle size reduction to energy requirements (Ref. 3). "Kick's Law" states that the work required for crushing a given material by a given

reduction ratio (diameter reduction is constant irrespective of the original size). "Rittinger's Law" states that the work consumed for particle size reduction is directly proportional to the new surface produced. A third law, regarded as "Bond's Law" falls between the other two laws. The technology is unclear as to the limitations and bounds of each of these three laws. One reference used by BCL indicates that Kick's Law applies at the larger particle sizes, Bond's Law applies to particle sizes of about one millimeter and that the relatively steep slope of Rittinger's Law applies to the micron particle sizes. However, the general technology does not categorize the laws to apply to specific particle sizes. Bond's Law can be expressed as:

$$E = E_x \frac{\sqrt{X_f} - \sqrt{X_p}}{\sqrt{X_f}} \sqrt{\frac{100}{X_p}}$$

$E_x$ = Average work index, kwh/ton

$X_f$ = Diameter of 80% of feed particles, microns

$X_p$ = Diameter of 80% of product particles, microns

Since values for $E_x$ are available, Bond's Law is readily usable. As a check that Bond's Law is applicable to the micron particle sizes, Table B compares some empirical data to calculated data. This Table attempts a nominal correlation of measured to calculated energy requirements despite a lack of validly comparable data. Some empirical data exists on grinding energy requirements for anthracite coal but no such data is readily available for coal or fluid petroleum coke. However, Grindability Indexes are available for coal and fluid petroleum coke. The Hargrove Grindability Index of fluid petroleum coke is similar to that of

Table B. NOMINAL COMPARISON OF CALCULATED VERSUS MEASURED GRINDING ENERGY FOR SELECTED MATERIALS

| Material | Hargrove Grindability Index | Average Work Index, Ei (Kwh/ton) | Product Size $X_p$ (microns) | Grinding Work Required, Kwh/ton | |
|---|---|---|---|---|---|
| | | | | Measured | Calculated (E) |
| Coal | 100 | 11.37 | 4 | | 56.85 |
| Fluid Petroleum Coke | 20-30 | 38.60 | 6.1 - 7.3 | | 152 - 143 |
| Anthracite | 26 | (38.60)* | 6.1 - 7.3 | 246 - 330 | |
| Iron Oxide | | 15.44** | 74 | 17 - 23 | 18 |
| | | 15.44 | 45 | 33.5 - 54 | 23 |
| Gypsum Rock | | 8.16 | 160 | 6.25 - 13.1 | 6.46 |
| Phosphate Rock | | 10.13 | 74 | 10.1 - 26.3 | 11.7 |

*Based on the similar Hargrave Grindability Index of fluid petroleum coke.

**Based on Iron Ore Work Index

$E = Ei \sqrt{\frac{100}{X_p}}$, from Bond's Law for $X_F >> X_p$; that is, for relatively large feed sizes and therefore large reduction ratios.

anthracite coal. Consequently, the actual work requirement for fluid petroleum coke should correlate with that for anthracite coal for the same overall material size reduction. The calculated results for the given selected materials, indicates that the Bond Law for grinding energy appears relatively applicable to grinding products to 74 microns (200 mesh). The Bond Law appears to underestimate the energy requirements as product particles are reduced below 74 microns. In particular, the energy required to grind anthracite coal to 6 to 7 microns is twice the calculated energy required to equivalently reduce fluid petroleum coke which should have a grindability similar to that of anthracite coal based on similar hardnesses.

Another approach is to use the "Energy Coefficient," based on Rittinger's Law, to estimate the pulverizing energy required for coal. The value of this coefficient should be between 0.02 to 0.10 tons/hp-hr for pulverizing hard to medium hard materials to No. 200 sieve size (74 microns). Coal is normally classed as a medium hard material and could therefore be applicable. Consequently,

$k = 0.02$ to $0.10$ tons/hp-hr

$1/k = 50$ to $10$ hp-hr/ton

$1/k = 37.28$ to $7.457$ kwh/ton for hard to medium hard materials, respectively.

Rittinger's Law is:

$$E = C\left(\frac{1}{X_p} - \frac{1}{X_f}\right)$$

where

$$X_f >> X_p, \quad E = C\left(\frac{1}{X_p}\right).$$

Now if 1/k = 7.457 kwh/ton for a medium hard material such as bituminous coal, the "C" coefficient for coal can be determined by setting $1/k = E = C\left(\frac{1}{X_p}\right)$.

$$C \left(\frac{1}{X_p}\right) = 7.457$$

However, the Energy Coefficient applies only to reducing coal to 74 microns. Therefore, coefficient "C" becomes

$$C = 7.457 \ (74) = 551.8.$$

Now if "C" can be applied to a smaller particle range, Rittinger's Law can be used to estimate the energy required to reduce the 74 micron particles to 4 micron.

$$E = 551.8 \ (1.4 - 1/74)$$

$$= 551.8 \ (0.236)$$

$$E = 130.2 \text{ kwh/ton.}$$

The original energy required to pulverize coal to 74 microns should be added to that required to further grind it to 4 microns. Consequently, the very minimum energy required to reduce coal to 4 microns should be 137.657 kwh/ton.

Since limited information indicates that the Bond Law tends to calculate one-half the energy required for grinding to the small (approaching 4 micron) particle sizes, the calculated coal grinding energy of 56.85 kwh/ton indicated on Table B should be approximately doubled. The resulting gross estimate of the energy required to reduce coal to 4 microns would then be 114 kwh/ton. Although this value does not correlate well with the estimate using the "Energy Coefficient" (130.0 kwh/ton), the indication is that the energy required to reduce coal to 4 micron particles should be much greater than the 25 kwh/ton claimed feasible by ILOK

through their "special" coal power manufacturing process. The coal grinding energy could well exceed 100 kwh/ton to achieve the appropriate fineness requirement. However, the 250 kwh/ton value indicated by BCL seems to have been based on the energy requirement for grinding anthracite coal to 6 or 7 microns (refer to Table B and Ref. 3). This energy requirement estimate appears too high for bituminous coal which has a grinding work index less than one third that of an anthracite coal (Table B). Based on the limited information generally available on pulverizing and grinding technology, the energy required to pulverize and grind bituminous coal to a 4 micron size could be estimated to be between 125 to 175 kwh/ton with a reasonable degree of confidence. A nominal value of 150 kwh/ton grinding energy could be considered representative of the energy required to reduce coal to 4 micron powder.

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